

## 2003 Steven V. Szabo Award for Engineering Excellence Recipient

### High-Flow Jet Exit Rig Design Team

James E. Bridges  
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For designing and developing a jet engine nozzle test rig capable of measuring thrust and flow in a realistic flight environment

The aeroacoustics and aeropropulsion research test community requires an increasingly demanding set of capabilities for simulation of single-flow jet nozzles. To meet this challenge, the High-Flow Jet Exit Rig Design Team was tasked with designing a single jet rig that supplies hot gases to nozzle system models quietly and measures the flows and forces to within very small tolerances, while placing the nozzle system in a realistic flight environment and still being flexible enough to accommodate NASA's wide range of research needs. The nozzle system must sit in the middle of a mach 0.3 flow with only as much supporting structure as an engine mount would provide.

The High-Flow Jet Exit Rig Design Team designed a rig capable of supplying airflow ranging from 530 °R at 29.1 lbm/s up to 1960 °R at 16 lbm/s. These flows are enough to produce a maximum nozzle thrust load ranging from 500 to 2000 lbf. The system required a measurement of the thrust load to an accuracy of  $\pm 0.25$  percent and flow metering accuracy to  $\pm 0.25$  percent of full scale. Additionally, this facility has the added advantage of being able to test both single-flow and dual-flow nozzles without compromising force-balance measurement capability.

In order to meet these challenging requirements, the rig was designed to be robust enough to test nozzles under very severe operating conditions with virtually no water cooling, yet nimble enough to measure thrust loads accurately with repeatability. Even with a total system weight of around 3000 lb, the test apparatus fabricated from Hastelloy-X was engineered to essentially float in the axial direction to allow for unrestrained movement from thermal growth (1.8 in.) while creating a deterministic path for translation of thrust loads into a load cell. The Hastelloy-X construction withstands the temperatures and pressure (450 psig) without the need for water cooling—reducing assembly, maintenance, and operational costs. The hardware is designed to the maximum allowable limit of the industrial standard piping code ASME B31.3.

The challenge of minimizing upstream noise sources is often encountered when designing for nozzle noise testing. A quiet flow was required such that jet noise from nozzle systems capable of 20 dB suppression can be measured without contamination at aircraft approach condition. Innovative design measures were taken to address this requirement. The supply tubes were individually

manufactured from solid rods of Hastelloy to allow an unconventional bend radius for expansion loops that also minimized the noise encountered from small radius bends. Additionally, a quiet 7-in.-diameter choke plate was engineered by machining 10 000 microdrilled holes (0.033 in.) through the 0.75-in. plate. This will create a quiet flow within the core supplied to the nozzle, while contoured end caps and internal ramps deflect sound waves back upstream prior to the nozzle entrance.

The heater/combustor required special attention to ensure complete and effective combustion would occur over the full range of operating conditions. Many combustors were evaluated and the J-79 was selected. The J-79 is the engine in the F-4 Phantom. The J-79 was modified to burn natural gas to reduce emissions and is more laboratory friendly.

In the world, there are good jet acoustic rigs, rigs quiet enough to meet the NASA mission, as well as good thrust stands rigs that are never reconfigured for fear of disturbing their calibration characteristics. Additionally, there are good flow diagnostic rigs, but they do not run hot because of the inherent difficulty in seeding hot flows. The High-Flow Jet Exit Rig at the NASA Glenn Research Center is unique in that it combines all these attributes and does so in a flight environment with true far-field acoustic measurements. It has required many talented individuals several years to innovate and optimize a solution that can support the wide mission NASA requires of this rig. From engineering clean burning combustor systems to optimizing thrust stand configurations for hot operation to gleaning the flow path for unwanted noise sources, the rig represents an achievement of multidisciplinary engineering teams committed to excellence against contradictory requirements.

## 2004 Steven V. Szabo Engineering Excellence Award Recipient

### The Rotating Microphone Rake Team

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For the design of a revolutionary acoustics measurement system that has become an indispensable diagnostic tool for characterizing the modal structure of noise inside a fan duct

The Rotating Microphone Rake is a revolutionary acoustics measurement system that was designed to fill a need in aeroacoustics research. Acoustic researchers at Glenn Research Center were aware that turbofan noise from all modern commercial jet engines propagates as spinning acoustic modes and harmonics based on the fan rotor-stator blade interactions. The need for accurate measurement of fan-generated spinning modes and their harmonics was conceptualized in several research papers. However, no one was able to accurately measure this phenomenon. This team solved the problems of measuring spinning acoustic modes by inventing this unique rotating microphone instrumentation system. This rake comprises a large geared ring that surrounds an engine inlet with a microphone rake that rotates around the ring taking acoustic measurements. It is synchronized with the rotation of the engine fan. This system now allows for quick data collection and acquires hundreds of megabytes of useful acoustic data in mere minutes. The rig is easily configured to any model in the 9- by 15-Foot Low-Speed Wind Tunnel (9315 LSWT) since the rake drive system remains unchanged while the variable-length structural tie-ins can be adapted to any model's nacelle. Since the rake is not mechanically geared to the model rotor it can be easily used on any model. The team's April 2003 test of the Source Diagnostics Test (SDT) model entry represented the culmination of many earlier successes that have been built on by this acoustics measurement system.

The engineering team solved the problems of measuring spinning acoustic modes by inventing this unique rotating instrumentation system. They surmounted the technical difficulties of sweeping a rake around a turbofan inlet and exhaust duct very precisely synchronized to the fan rotor (rake-to-fan error less than  $0.2^\circ$  per fan rotation with less than  $0.2^\circ$  of total drift in 50 000 fan revolutions) without mechanically gearing the rake to the rotor itself. This accurate rotation takes advantage of the Doppler shift which separates these spinning harmonics into separate measurable sources. The useful data from this unique rotating rake system has led to publication of over 30 papers. Fan noise on Pratt & Whitney, Rolls-Royce Allison, AlliedSignal (Honeywell), and General Electric engine models and most recently on the SDT (2000) and Quiet High

Speed Fan (2001) were successfully measured in the 9315 LSWT by this team using the Universal Rotating Rake. This data was instrumental in both verifying NASA acoustics computational fluid dynamics (CFD) codes as well as retiring inaccurate ones. According to Dennis Huff, the acting Structures and Acoustics Division chief, the rotating rake was “. . . the main measurement we used to show our old prediction code (V072) was insufficient and our new code (LINFLUX) provides good accuracy sometimes within

1 dB.” Rotating rakes were also built into the Active Noise Control Fan rig, and recently a larger version of the rotating rake was built and tested for AlliedSignal under a technology transfer opportunity on an AlliedSignal

TFE 731–60 engine undergoing acoustic testing in Phoenix, AZ. In addition to successfully determining the acoustic signature of the commercial engine the rotating rake system (hardware, software, and operating procedures) were transferred to AlliedSignal as well. As a result of the team’s work in resolving engineering problems, the test program and technology transfer of the rotating rake was successful. The team also began dialog in January 2003 with General Electric Aircraft Engines who has requested use of this valuable technology. The team has received other requests from Purdue University and Langley Research Center to transfer this technology to help them increase their understanding of acoustic modes.

The team was responsible for test-qualifying rotating rakes for use directly upstream of high-speed fan blades susceptible to numerous technical and safety hurdles both at the wind tunnel level and full-size engine level. They conducted qualification tests in the Glenn Structural Dynamics Laboratory and CE–12 free-jet cell (to verify aeroelastic stability) and conducted detailed aeroelastic and finite element analyses to fully qualify these rakes. The team also was able to solve data acquisition complexities from as many as 12 pressure transducers gathering data and get that massive amount of data off the rotating platform without loss of data fidelity. This was accomplished using a bank of 12 custom, dual-channel modules of commercial telemetry, which obviated the need for expensive and cumbersome data slip rings. After the data was acquired, a narrow-band frequency analysis and Bessel function curve fitting of data was completed to correctly portray the acoustic structure of the fan-stator interaction noise. The complexity of the overall system has led to several technology transfer opportunities to industry partners who were not confident in pursuing these risks themselves.

In an unsolicited letter of commendation the vice president of advanced engineering programs at Pratt & Whitney said of the rotating rake system, “The technical firsts during this 8-month program are numerous. Most notable is the measurement of source noise with the inlet rotating microphone rake.” Also, in a letter of commendation from the chief of Glenn’s Acoustic Branch, both Glenn and Pratt & Whitney management expressed how “pleased and impressed (they) were with the initial test results and the entire 9’315’ mode measurement operation.” Never before had spinning modes been measured accurately until the rotating rake was invented.

## 2005 Steven V. Szabo Engineering Excellence Award Recipient

### Parametric Inlet Team

Michael A. Ernst  
David R. Root  
Robert Sanders  
John D. Sanders  
John W. Slater  
Paul A. Solono  
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For innovative design and fabrication of an advanced external compression supersonic inlet for aircraft engines

An advanced supersonic external compression inlet for aircraft engines was conceived, designed, fabricated, and tested at NASA Glenn Research Center with high-quality results. Potential applications of this inlet include supersonic military and civilian cruise vehicles and high-speed cruise missiles. With the end of the High-Speed Research (HSR) program, funding sources for supersonic inlet design were greatly reduced. To ensure that this did not lead to a precipitous loss in supersonic inlet design and analysis capability, NASA Glenn decided to pursue this innovative alternative inlet design. This concept, referred to as the Parametric Inlet, has the potential to overcome some of the shortcomings of the previously selected HSR inlet concept. This work culminated in a wind tunnel test of the inlet model that validated the overall design approach.

The Parametric Inlet design was the culmination of excellent teamwork across a wide matrix of disciplines including computational fluid dynamics (CFD) analysts, aeronautic researchers, mechanical design engineers, machinists, and operations and test cell technicians. Mechanical design and aeronautic researchers iterated on the flow shape using CFD results. The ability to collaborate on this highly three-dimensional design was enhanced by using advanced computer-aided design solid-modeling tools and rapid-prototype-manufactured models. The Parametric Inlet's mechanical design was based on the unique "hull" concept, brought about by the shape and changeover requirements of the Parametric Inlet. At Glenn, typical supersonic research inlets have been built up as multiple, coaxial spools. The initial concept for the Parametric Inlet started out with this traditional approach, but was discarded as the design progressed when it became obvious that this nonconventional inlet would require lengthy changeover times if something radically different was not tried. With the hull concept, the stationary hardware is attached to the hull. The movable hardware (motion assembly) is attached to the strongback. The motion assembly can be separated from the stationary hardware in about 1/2 hr. During testing it allowed for quick changeovers, which were significantly shorter in time than with the traditional spool design, taking hours as opposed to several days.

That meant more testing was accomplished in less time, yielding a substantial cost savings in the 10- by 10-Foot Supersonic Wind Tunnel. This unique design contributed to a reduction of the test cell occupancy from 3 to 6 months down to 8 weeks.

The Parametric Inlet has the promise for comparable performance with lower weight and part count, lower bleed rates, low cowl drag, reduced complexity, and increased safety. This technology directly aligns with the Aeronautics objectives to increase capacity and mobility by enabling more people and goods to travel faster and farther with fewer delays. This project was also the first to make significant use of the NASA Fabrication Alliance to fabricate the many parts needed for the assembly. Parts were fabricated in machine shops from NASA centers Glenn, Ames, Langley, Marshall, and Goddard.

The difficulty of this project was in responding simultaneously to three demanding requirements: a complex flow path shape, variable geometry, and unique sealing. The shape of the inlet went from sectorized to circular, so the transition between those two sections resulted in a complex, contoured flow path. There was a need for variable geometry along the ramp side (top) of the flow path. In effect, large segments of the flow path had to be able to be moved. There was a need to provide compartmentalized bleed to four locations on the inlet. To obtain meaningful research data, this meant that sealing between these compartments was critical. Custom D-seals and an inflatable curtain seal were tested and designed to accommodate the unique shapes and large ranges of motion. Data from the wind tunnel tests verified the soundness of this design. The complexity of the system was a result of satisfying these requirements simultaneously. The subsystems needed to perform their functions throughout the entire range of motion of the ramps as well. In addition, the ramp actuation system had to be compact as it was designed for the confined space above the supersonic diffuser. Lastly, care needed to be taken to integrate the motion assembly through the sealed, compartmentalized bleed regions. The resulting inlet was a compact, tightly integrated system that successfully underwent rigorous research testing in the demanding environment of the wind tunnel.

A significant technical achievement has been realized with the completion of testing of the Parametric Inlet, an innovative supersonic inlet for tomorrow's advanced propulsion systems. This advance in the state-of-the-art of supersonic external compression inlet design has the potential to overcome shortcomings of the inlet concept previously selected by the HSR program, NASA's most recent effort to develop a high-speed civil transport.